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RESEARCH MEMORANDUM

AN APPROXIMATE METHOD FOR CALCULATING THE EFFECT OF SURFACE ROUGHNESS ON THE DRAG OF AN AIRPLANE

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
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AN APPROXIMATE METHOD FOR CALCULATING THE EFFECT OF SURFACE ROUGHNESS ON THE DRAG OF AN AIRPLANE

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SUMMARY

A method for computing the effect of surface roughness on the drag coefficient of an airplane is presented. Calculated results using this method are compared with experimental results from both flight and wind-tunnel tests. In general, the agreement is believed satisfactory.

INTRODUCTION

Considerable research has been performed in the past to determine the effect of surface roughness on the drag of an airplane or its component parts. In general, however, these data have been limited to several degrees of roughness and types of airplanes. In order to determine the effect of other degrees of roughness on a specific airplane, the designer must therefore resort to further experimentation or attempt to estimate the effect. In order to provide means to estimate the effect of various degrees of roughness on any airplane, the method discussed in this report was developed. The method combines several relations used in determining the skin-friction drag of flat plates with various surface conditions.

SYMBOLS

The following symbols are used in this report:

C_f skin-friction drag coefficient (The coefficient is based upon the area for which the drag is being computed.)

x length in direction of air flow of that part of a surface for which drag coefficient is being computed, feet

K height of roughness particles on surface, feet

K_s equivalent sand grain height, feet

R Reynolds number $(V_o x/\nu)$

R_δ boundary-layer Reynolds number $(V_o \delta/\nu)$

R_c wing Reynolds number $(V_o c/\nu)$

R_L body Reynolds number $(V_o L/\nu)$

δ distance normal to surface from the surface to a point in the boundary layer at which u equals $0.707V$, feet

c chord of wing, feet

s distance along surface from leading edge, feet

s_m distance along surface from leading edge, to point of maximum velocity, feet

L length of body, feet

r distance of surface from axis of revolution, feet

r_1 value of r at point for which boundary-layer thickness is being computed, feet

u velocity of air in boundary layer, feet per second

V_o free-stream velocity, feet per second

V_m maximum velocity over surface, feet per second

V_s velocity at point of laminar separation, feet per second

V velocity outside boundary layer, feet per second

V_1 value of V at point for which boundary-layer thickness is being computed, feet per second

ν kinematic viscosity of air, square feet per second

a,b constants

METHOD OF CALCULATING DRAG INCREMENT

General Discussion

The drag of a surface due to skin friction arises from the momentum losses in the boundary layer. The momentum losses in the boundary layer are dependent not only on the extent of the surface upstream of the point at which the losses are measured, but also on the type of flow in the boundary layer. In this particular discussion three different types of boundary-layer flow are of interest, namely, laminar flow, turbulent flow over a smooth surface, and turbulent flow over a rough surface. To illustrate these types of flow, assume that air is flowing over a surface, the forward portion of which is smooth and the latter portion rough. The growth of the boundary layer along this surface would be as follows:

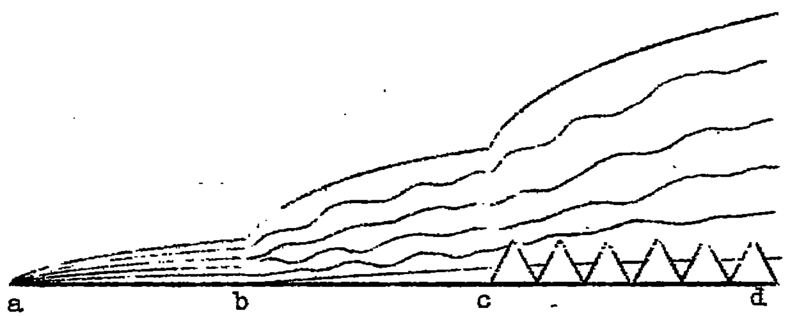

Diagram 1

At point a, the leading edge of the plate, the boundary-layer thickness is zero. From points a to b the boundary layer is laminar. Transition is assumed to occur at point b, causing a turbulent boundary layer on a smooth surface to exist from points b to c. In actual practice complete transition will not occur at a point. Notice that beneath the turbulent boundary layer there is a thin laminar sublayer. The roughness particles project above this laminar sublayer behind point c. A turbulent boundary layer on a rough surface exists, therefore, from c to d.

In order to compute the drag of this surface, it is necessary to know the decrease in boundary-layer momentum in unit time as the air passes from point a to point d. The momentum losses from the leading edge of the plate to any point on the plate can be shown as the ordinate of a curve plotted in relation to the length of the plate, as shown in diagram 2. It will be noticed that there are three different curves corresponding to the three types of flow over the flat plate.

Various equations have been determined analytically and empirically from which the ordinates of these curves can be found, provided the conditions set forth in the derivation of these equations are met. These conditions are as follows:

1. The boundary layer must be the same type as that used in the derivation of the equation.

2. The same type of boundary layer must extend over the entire surface.

3. The momentum losses in the boundary layer must be zero at the upstream edge of the surface.

An inspection of diagram 2 shows that only condition 3 is met since three different types of boundary layer occur on the plate and therefore no one equation could be used for all three types.

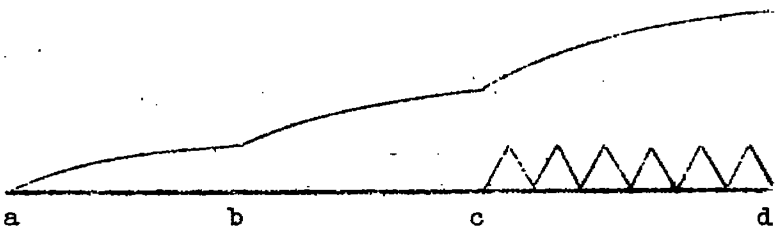

Diagram 2

For the purposes of the calculation let the plate be divided into three sections, each surface having only one type of boundary layer as shown in diagram 3.

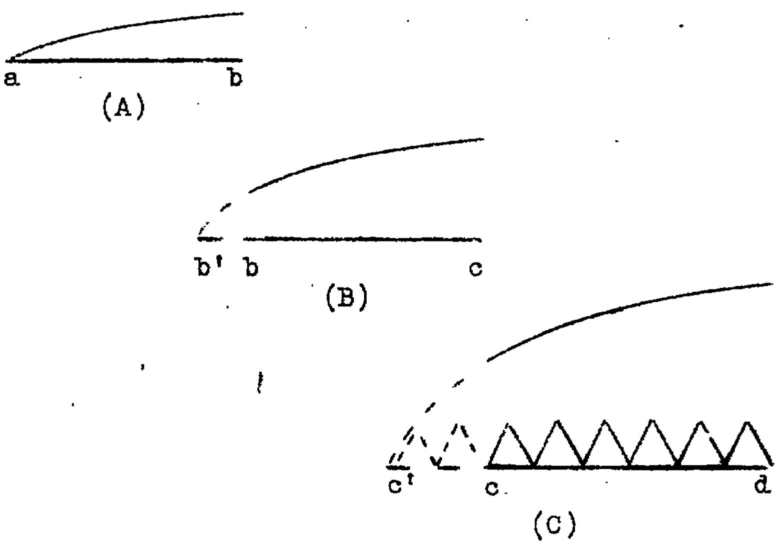

Diagram 3

It is then possible to meet conditions 1 and 2 for each surface separately, but condition 3 is fulfilled only for the most upstream surface (surface A). However, if the middle and downstream surfaces (surfaces B and C) were extended upstream to a point at which the momentum losses in the type of boundary layer under consideration theoretically would be zero, the flow over this enlarged surface would fulfill condition 3 and the momentum losses at any point on the surface could then be calculated. The momentum losses in the boundary layer over the extended part of the surface are shown by dotted lines in diagram 3.

It will be noticed in diagram 3 that the momentum losses at point b are identical on surfaces A and B and that the losses at point c are also identical. This characteristic then simplifies the determination of lengths b'b and b'c, for since the momentum losses at point b can be determined from the equation appropriate to the flow over surface A, it is only necessary to substitute this momentum loss in the equation appropriate to the flow over surface B and determine the length of flow required to produce the loss. The loss at point c is then determined by using the length b'c in the equation appropriate to surface B.

It therefore can be seen that the determination of the momentum losses in the boundary layer at point d, which is equal to the drag of the plate, is a step-by-step process when more than one type of flow exists over the plate. An outline of this process and a numerical example are shown in the appendix.

Basic Equations

The basic skin-friction drag equations as given in the references are as follows:

For a laminar boundary layer, the equation is

$$C_f = \frac{1.327}{\sqrt{R}} \tag{1}$$

For a turbulent boundary layer on a smooth surface the equation is

$$C_f = \frac{0.455}{(\log_{10}R)^{2.58}} \tag{2}$$

For a turbulent boundary layer on a rough surface the equation is

$$C_f = \left(1.89 + 1.62 \log_{10} \frac{x}{K_s}\right)^{-2.5} \qquad (3)$$

To facilitate the use of these equations in the method previously discussed, it is more appropriate that they be given in terms of drag than drag coefficient. Moreover the drag coefficients in the preceding equations are based upon the area for which the drag is being computed. In general, the coefficients will be based on the projected wing area of the airplane. Presenting the equations in terms of drag then makes it easy to base the coefficients on the wing area by dividing by this area at the conclusion of the calculation.

The equations are, therefore, modified by multiplying by a length term as follows:

$$C_f x = \frac{1.327\sqrt{x}}{\sqrt{R/x}} \qquad (4)$$

$$C_f x = \frac{0.455x}{[\log_{10}(R/x) + \log_{10} x]^{2.58}} \qquad (5)$$

$$C_f x = \frac{x}{[1.89 + 1.62 \log_{10}(x/K_s)]^{2.5}} \qquad (6)$$

The term $C_f x$ is then the drag per unit width of the plate divided by the dynamic pressure. The term R/x is used since it is a function only of the true airspeed and the kinematic viscosity of the air. Its value is shown in figure 1. In figures 2 to 4 the values for equations (4) to (6) are shown.

Equation (4) is the Blasius relationship (reference 1, p.322) and is used only when a laminar boundary layer exists on the surface. Equation (5) is used (reference 1, p. 324) whenever the flow is over a smooth surface and has a turbulent boundary layer. When the flow is over a rough surface and has a turbulent boundary layer, equation (6) is used (reference 2). Equation (6) is independent of Reynolds number. It may be used, however, only when the Reynolds number is sufficiently large to cause the laminar sublayer beneath the turbulent boundary layer to be small in comparison to the height of the roughness particles. At small Reynolds numbers for which the laminar sublayer completely blankets the roughness particles, the flow is similar to that over a smooth surface and equation (5) may be used. Figure 5 shows the Reynolds number range in which the skin-friction drag coefficient becomes independent of Reynolds number and equation (6) may be used.

In figure 6 the effect of roughness density on the equivalent sand grain height is shown. The points on the curve are taken from data given in reference 2.

Determining the Type of Flow

In order to use the method previously discussed it is necessary to determine the types of flow over the surface and the length of each type of flow. On a smooth surface two types of flow may exist: the boundary layer may either be laminar or turbulent. From the stagnation point to the transition point the boundary layer is laminar. The problem then becomes one of determining the location of the transition point at which the laminar layer will transform into a turbulent layer.

In some cases, the transition point will have been determined experimentally, thereby eliminating the problem. If such is not the case, approximate methods must be used.

On low-drag wings and smooth bodies of revolution, reference 3 states that transition will probably occur in the region in which the boundary-layer Reynolds number R_δ has a value between 8000 and 9500. However, transition is assumed to occur at the point of minimum pressure if R_δ is less than the previously mentioned values at that point. Reference 3 gives the following values for R_δ.

For two-dimensional flow, the value of R_δ is

$$\frac{R_\delta^2}{R_c} = (2.3)^2 \left(\frac{V_o}{V_1}\right)^{7.17} \int_o^{s/c} \left(\frac{V}{V_o}\right)^{8.17} d\,\frac{s}{c}$$

and for bodies of revolution, the expression is

$$\frac{R_\delta^2}{R_L} = (2.3)^2 \left(\frac{L}{r_1}\right)^2 \left(\frac{V_o}{V_1}\right)^{7.17} \int_o^{s/L} \left(\frac{V}{V_o}\right)^{8.17} \left(\frac{r}{L}\right)^2 d\,\frac{s}{L}$$

For airfoils having maximum velocity far forward, it is assumed that transition will occur at the point of laminar separation. The following method (reference 4) may be used to find the separation point. The forward portion of the chordwise velocity distribution is approximated by two straight lines. The region ahead of the maximum velocity is represented by

$$\frac{V}{V_o} = a\left(\frac{s}{c}\right)$$

and the region directly behind tho maximum velocity by

$$\frac{V}{V_o} = (a + b)\,\frac{s_m}{c} - b\left(\frac{s}{c}\right)$$

The point of separation is then determined from

$$\frac{V_m}{V_s} = \Phi_s$$

where Φ_s as a function of b/a is plotted in figure 7.

If the surface is in the wake of the wing, as for example the horizontal tail, or in the propeller slipstream, it is assumed that transition occurs at the leading edge of the surface.

The boundary layer over a rough surface is assumed to be turbulent except near the stagnation point. No data are available which show the extent that a rough surface will cause premature transition, although reference 5 shows that a single row of small projections near the stagnation point will not move the transition point forward to the projections. It was assumed, therefore, that for surfaces which are rough up to the stagnation point a laminar boundary layer exists at least to the point at which the local velocity reaches the free-stream velocity.

RESULTS AND DISCUSSION

A comparison of theoretical results using the method discussed in this report with experimental results is shown in table I following the appendix. In the theoretical results, the roughness height and density were estimated from photomicrographs or enlarged sketches of the roughened surface. The dashed curves in figure 4 show the equivalent sand grain heights estimated for references 6 and 7. They are the same order of magnitude as the roughness in references 8 and 9.

The experimental results were given in force and coefficient form in references 8 and 9. In references 6 and 7, the drag coefficient was calculated from the velocity, brake horsepower, and altitude data given and from the efficiency of a propeller similar to that used on the P-51B airplane. (See reference 10.) The data of references 6, 7, and 8 were obtained from flight tests. The data of reference 9 were obtained from wind-tunnel tests.

Considering the approximations that have been made in the method discussed in this report in order to maintain its simplicity, the agreement between experimental and computed results is believed to be satisfactory. In all but two cases, the calculated increment of drag coefficient is within approximately 20 percent of the experimental increment. In the two cases in which the agreement was poor, only 15 percent and 40 percent of the leading edge of the P-51B wing was roughened. This poor agreement is believed to be primarily due to an inability to estimate accurately the point of transition when the wing leading edge is roughened. Therefore when only a small portion of the leading edge is roughened, errors in the location of transition cause proportionately large errors in the drag computations. However, for a wing completely roughened, the error in the drag increment due to an error in the transition point becomes proportionately small. This condition suggests the fact that, if the leading edge of a surface is roughened, the method may be used successfully only if a major portion of the wing is roughened, but cannot be used successfully when only a small portion of the surface is roughened. On the other hand, when only the trailing edge of the wing is roughened, the method gives satisfactory results even when only 33 percent of the trailing edge is roughened, as in the case of the comparison of calculated results with those of reference 6.

CONCLUSIONS

A method of calculating the effect on drag of roughness on the surface of an airplane, based upon equations for the skin friction of a flat plate, is discussed in this report. A comparison of experimental results showing the effect of surface roughness with results obtained from this method indicates the following:

1. In most of the comparisons, the calculated increment was within 20 percent of the experimental increment.

2. Due to an inability to estimate accurately the extent that a roughened surface will cause premature transition, experimental and calculated results in which only the leading edge of the wing is roughened do not agree very well. This is not believed too serious since in most cases the entire wing will be roughened.

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APPENDIX

OUTLINE OF METHOD TO COMPUTE DRAG INCREMENT

To calculate the effect of surface roughness by the method discussed in this report, the surface is assumed to be a flat plate and the skin friction of the plate in a smooth and a roughened condition is computed. The difference in these results is the increment due to surface roughness. An outline of the steps required to calculate the drag of a surface with two types of flow is as follows:

1. Determine types of flow of the surface and divide the surface into sections corresponding to the various types of flow.

2. Select the equation or figure applicable to each type of flow.

3. Calculate the skin-friction drag per unit width for the upstream section.

4. Find the distance that the second section must be extended upstream by substituting drag from step 3 into equation or figure corresponding to type of flow over second section.

5. Add distance from step 4 to length of second section.

6. Substitute length from step 5 into equation or figure corresponding to flow over second section. The result is the drag per unit width for the surface.

7. Multiply results of step 6 by the average width of the surface. The result is the skin-friction drag of the surface.

8. Since by using equations (4) to (6) or figures 2 to 4, the drag per unit width already is divided by the dynamic pressure, a coefficient may be obtained from step 7 by dividing by the reference area.

If more than two types of flow exist on the surface, steps 4 to 6 are repeated for each additional type of flow with the difference that the drag used in step 4 is the drag per unit width of all surface upstream of the section under consideration.

A numerical example of the method will now be shown. Each step will be numbered to correspond to the outline of the method.

Problem:

What is the increase in drag coefficient due to roughening 50 percent of the trailing edge of a wing?

Given:

Wing chord, 10 feet
Wing span, 60 feet
Reynolds number per foot of chord, 1×10^6
Transition from laminar to turbulent, 30 percent chord on upper and lower surface
Height of roughness particle, 0.0005 foot
Spacing of roughness particle, 0.0015 foot
Using figure 6, the equivalent sand grain height is found to be 0.0010 foot.

The skin-friction drag for the roughened wing will first be computed.

Steps 1 and 2

Section	Length	Type of Flow	Equation	or figure
1	3	Laminar	(4)	2
2	2	Turbulent on smooth surface	(5)	3
3	5	Turbulent on rough surface	(6)	4

Step 3

$$C_{fx} = \frac{1.327\sqrt{3}}{\sqrt{10^6}} = 2.3 \times 10^{-3}$$

Step 4

$$2.3 \times 10^{-3} = \frac{0.455\ x}{[\log_{10} 10^6 + \log_{10} x]^{2.58}}$$

$$x = 0.5 \text{ ft}$$

Step 5

$$x = 0.5 + 2 = 2.5$$

Step 6

$$C_{f}x = \frac{0.455 \times 2.5}{[\log_{10} 10^{6} + \log 2.5]^{2.5}}$$

$$C_{f}x = 9.4 \times 10^{-3}$$

Step 4'

$$9.4 \times 10^{-3} = \frac{x}{[1.89 + 1.62 \log_{10}\frac{x}{0.001}]^{2.5}}$$

$$x = 1.15$$

Step 5'

$$x = 1.15 + 5 = 6.15$$

Step 6'

$$C_{f}x = \frac{6.15}{[1.89 + 1.62 \log_{10}\frac{6.15}{0.001}]^{2.5}}$$

$$C_{f}x = 33.6 \times 10^{-3}$$

Step 7

Since the drag of both upper and lower surface is desired and the flows are the same over each surface, the average width of the wetted area is twice the wing span.

$$\frac{\text{Drag}}{\text{Dynamic pressure}} = 33.6 \times 10^{-3} \times 2 \times 60 = 4.03$$

Step 8

$$C_D = \frac{4.03}{10 \times 60} = 0.0067$$

For the smooth wing steps 4' to 6' are eliminated and the length of the second section is 7 feet.
For this condition

$$C_D = 0.0047$$

The drag increment is then

$$\Delta C_D = 0.0020$$

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ΔC_D?

TABLE I.– COMPARISON OF EXPERIMENTAL AND CALCULATED RESULTS

Type of Roughness	Surface Covered	Percent of Surface Covered	Experimental data from reference	Experimental results	Calculated results
Camouflage paint	P-51B fuselage	100 percent	6	0.0018	0.0022
Camouflage paint	P-51B wing	33 percent of trailing edge	6	.0013	.0012
Camouflage paint	P-51B wing	60 percent of trailing edge	6	.0025	.0024
Camouflage paint	P-51B wing	100 percent	6	.0045	.0048
Camouflage paint	P-51B wing	100 percent	7	.0063	.0056
Camouflage paint	P-51B wing	67 percent of leading edge	7	.0044	.0043
Camouflage paint	P-51B wing	40 percent of leading edge	7	.0025	.0033
Camouflage paint	P-51B wing	15 percent of leading edge	7	.0009	.0023
Night fight paint	P-51B airplane	100 percent	8	.0059	.0046
Night fight paint	P-51B airplane	100 percent	8	.0076	.0073
Sand grain roughness	23012 wing	100 percent	9	.0045	.0051
Sand grain roughness	23012 wing	100 percent	9	.0030	.0024

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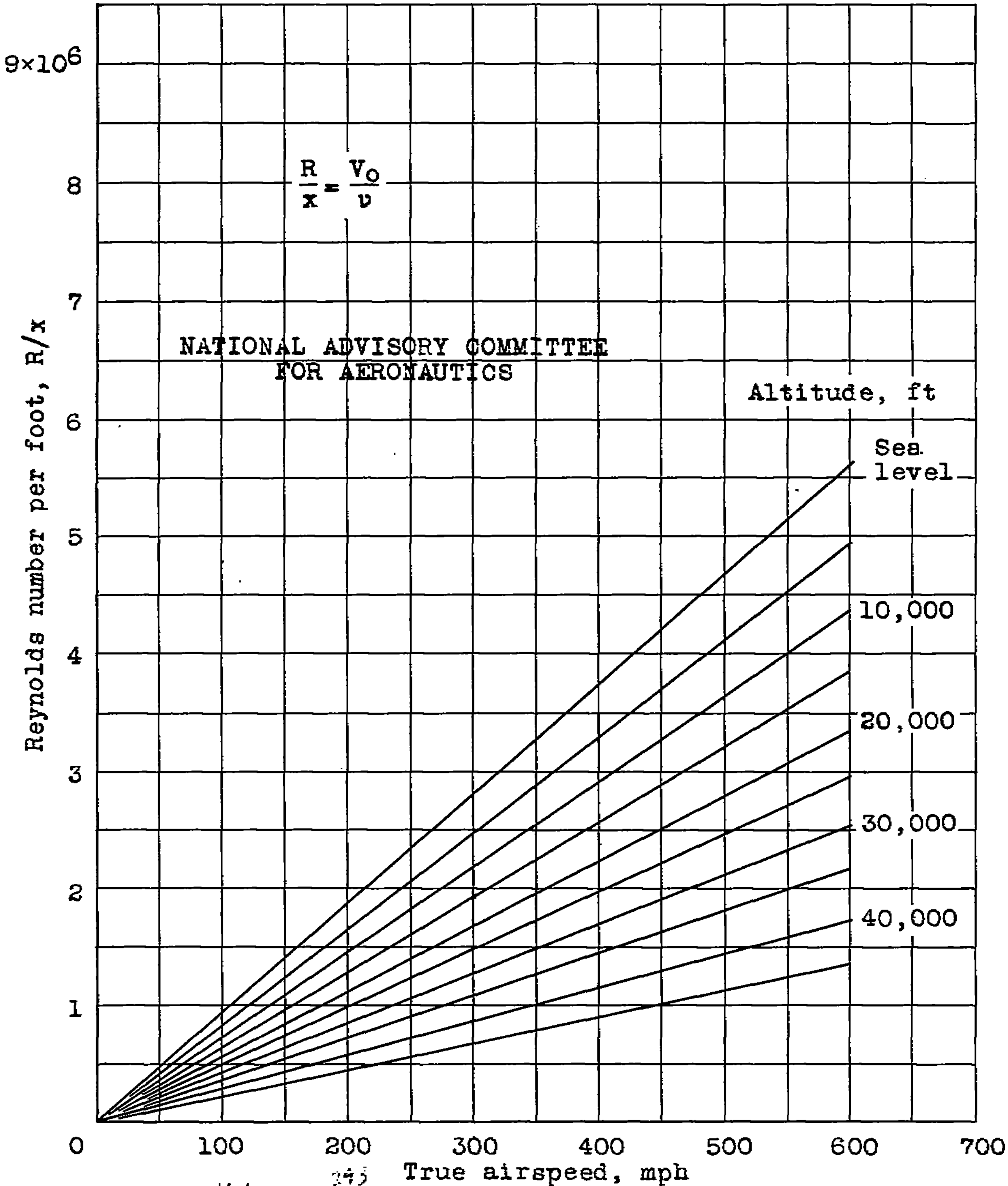


Figure 1.- Variation of Reynolds number with true airspeed.

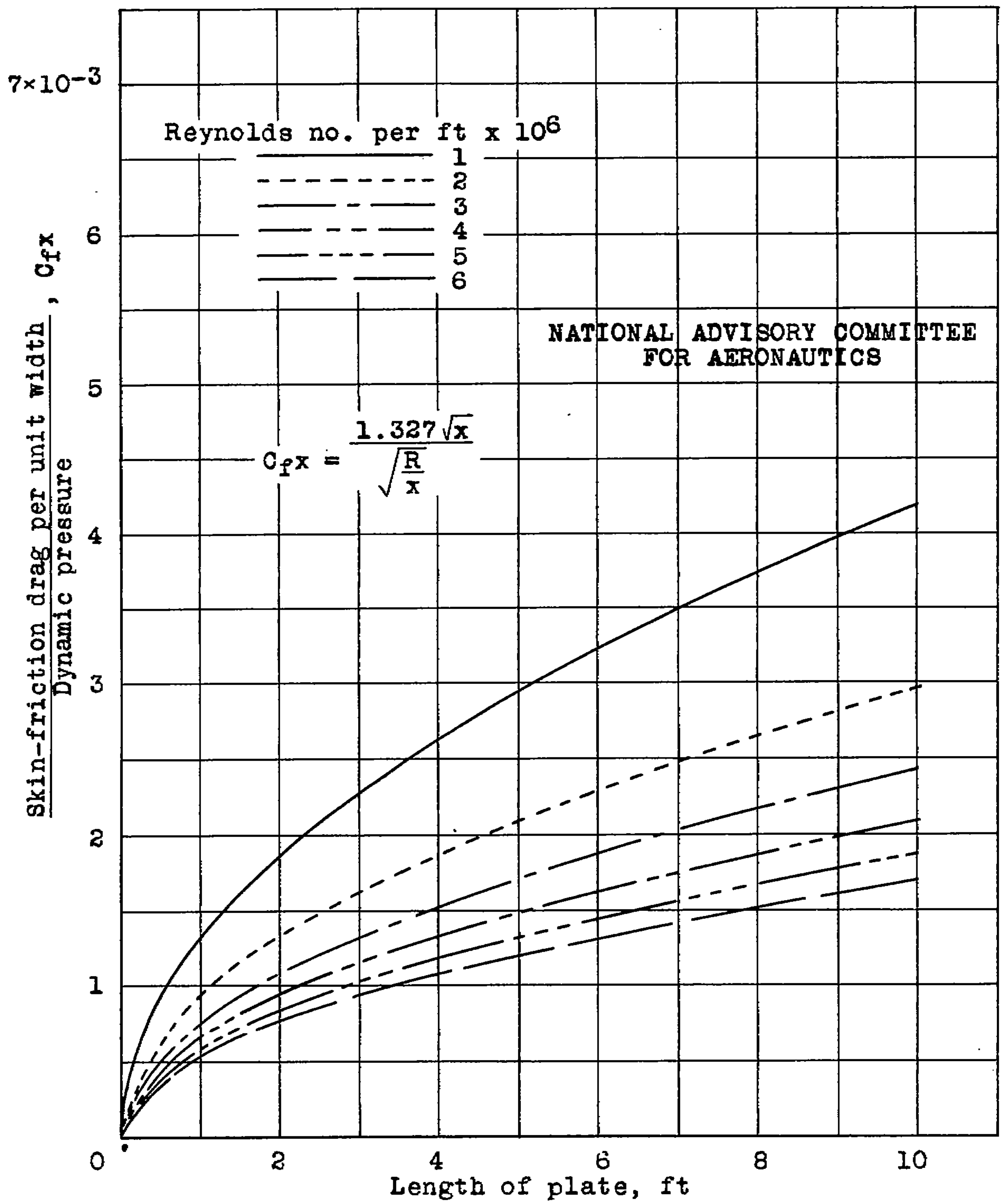


Figure 2.- The skin-friction drag of a flat plate for a laminar boundary layer.

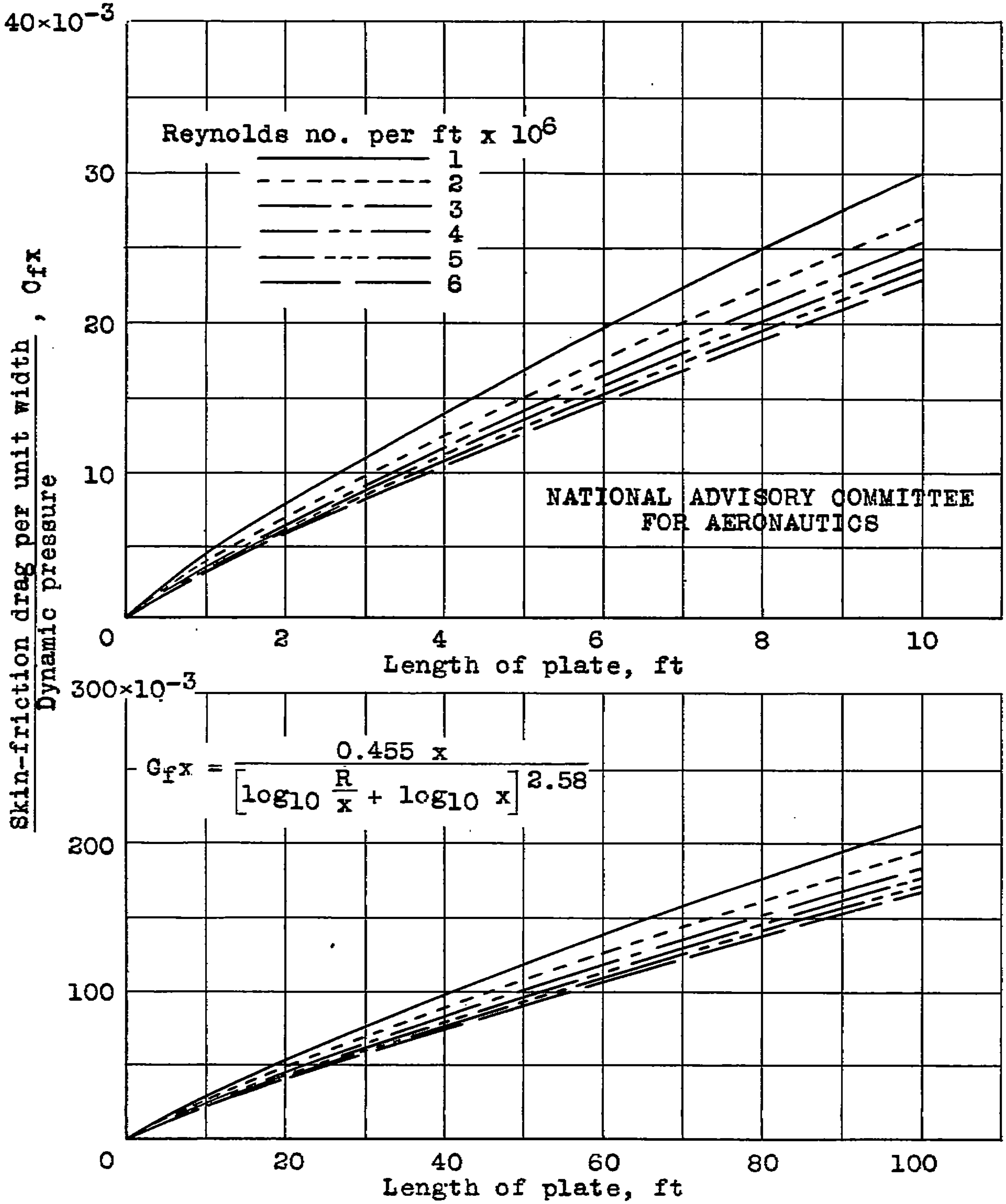
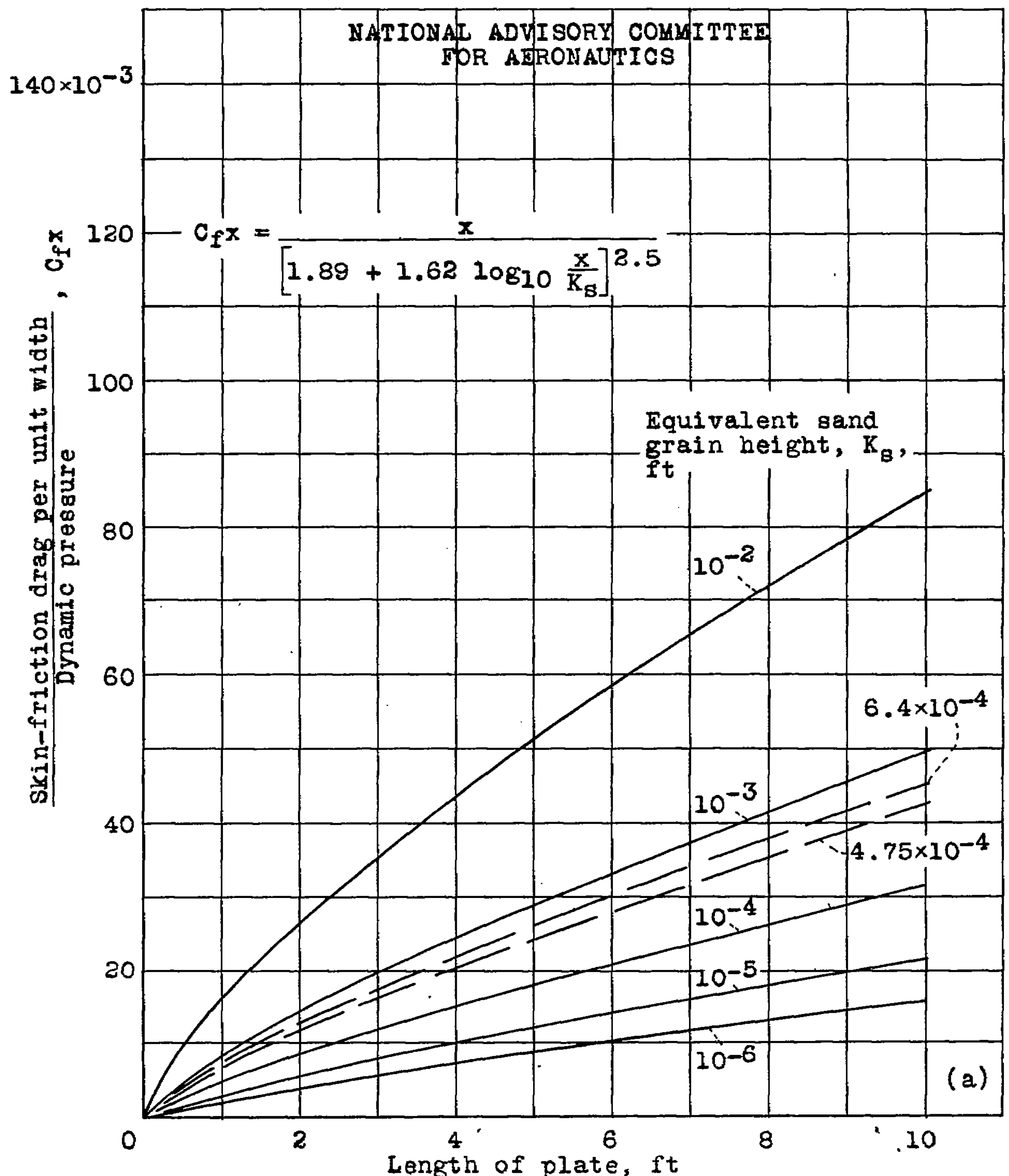
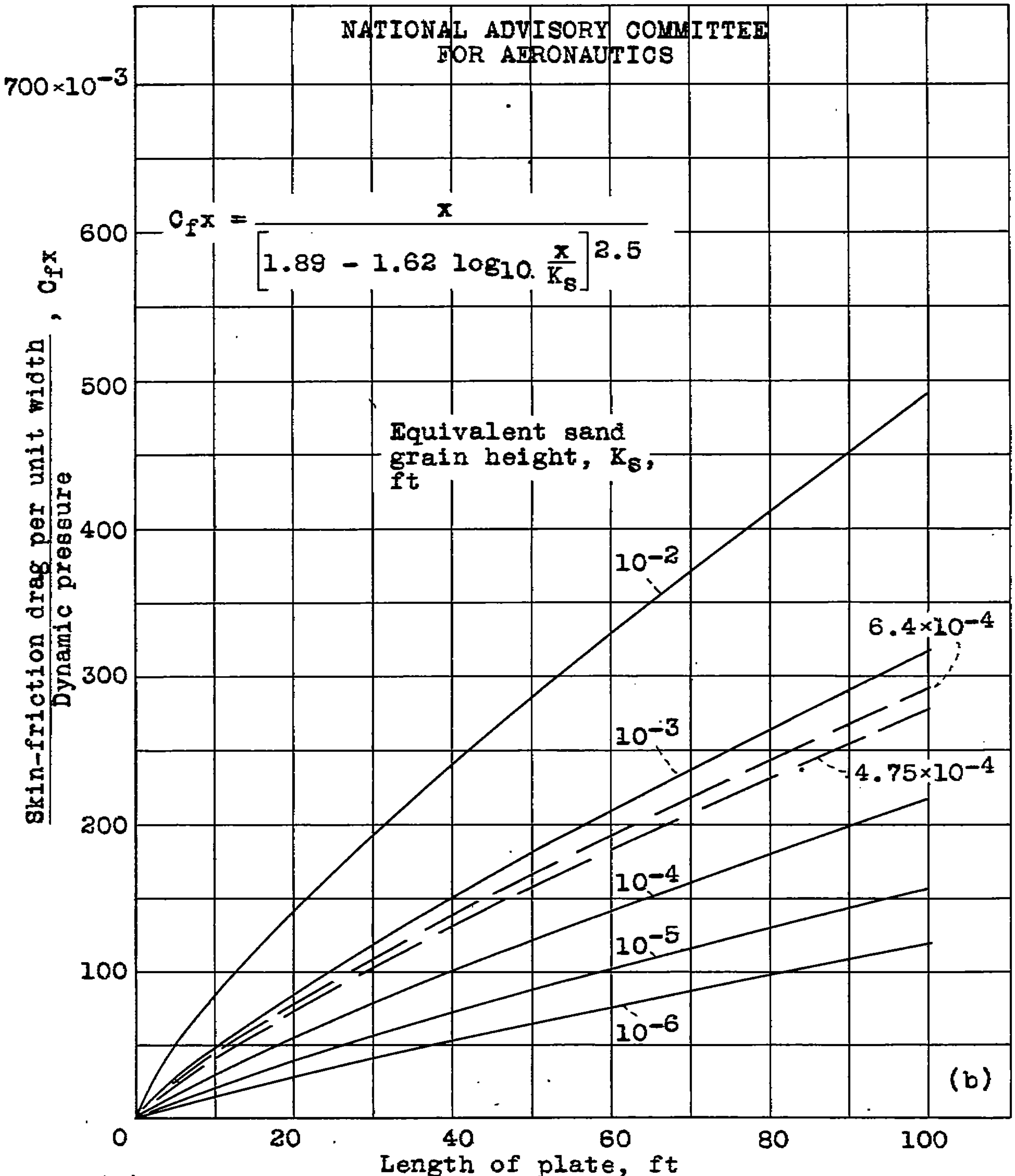


Figure 3.- The skin-friction drag of a flat plate for a turbulent boundary layer on a smooth surface.



(a) Lower range

Figure 4.- The skin-friction drag of a flat plate for a turbulent boundary layer on a rough surface.



(b) Upper range

Figure 4.- Concluded.

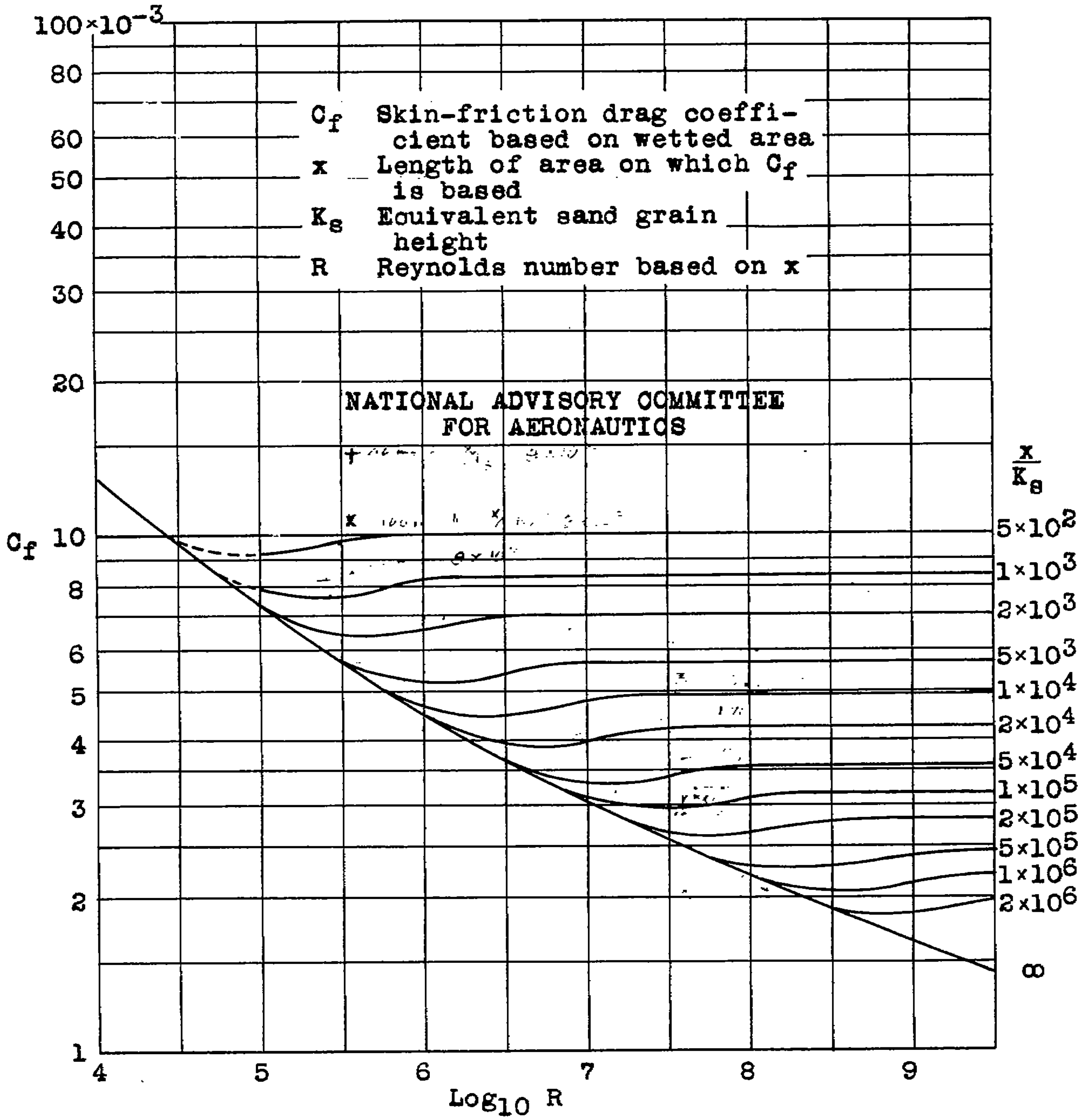


Figure 5.- Variation of skin-friction drag coefficient of a flat plate with Reynolds number for a turbulent boundary layer on a rough surface.

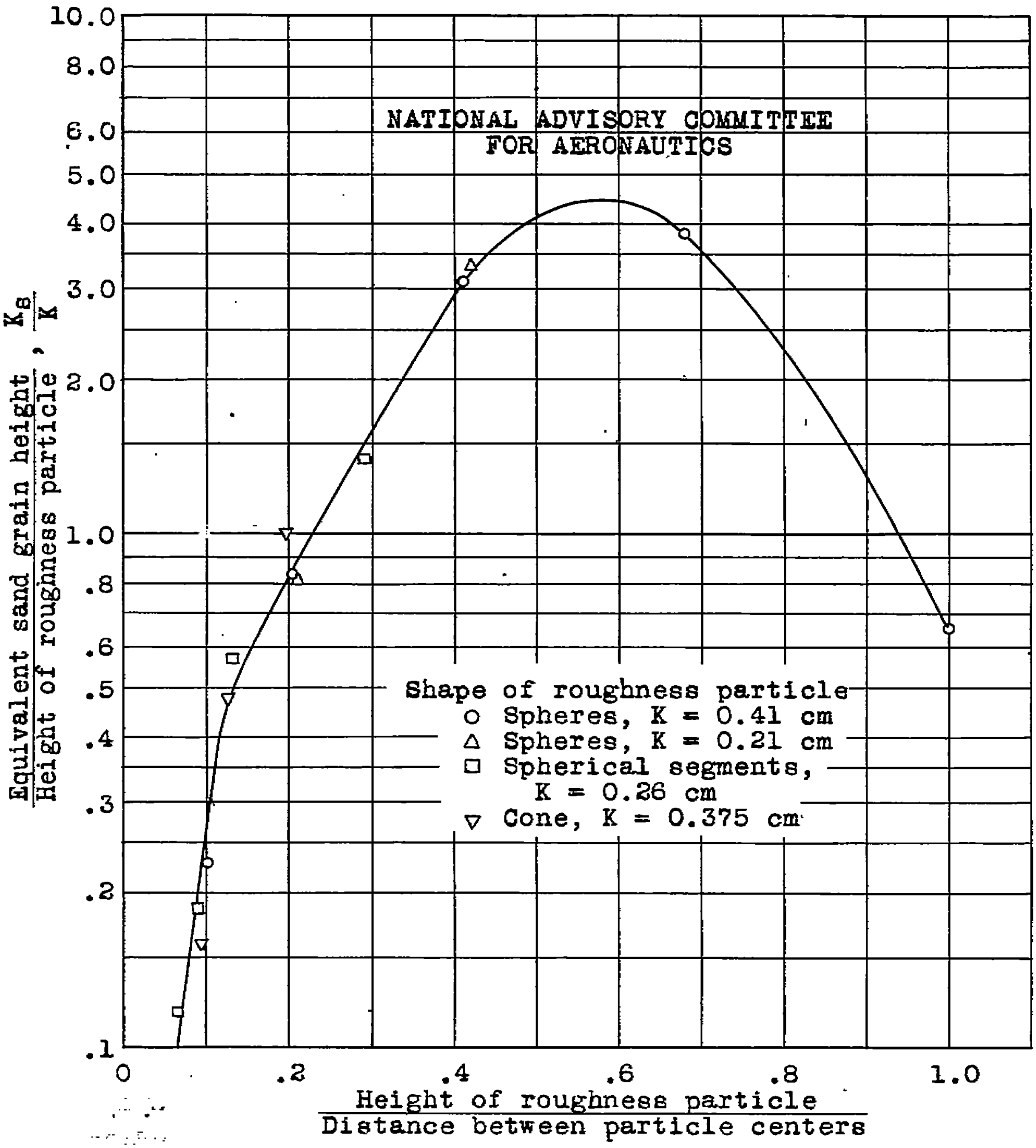
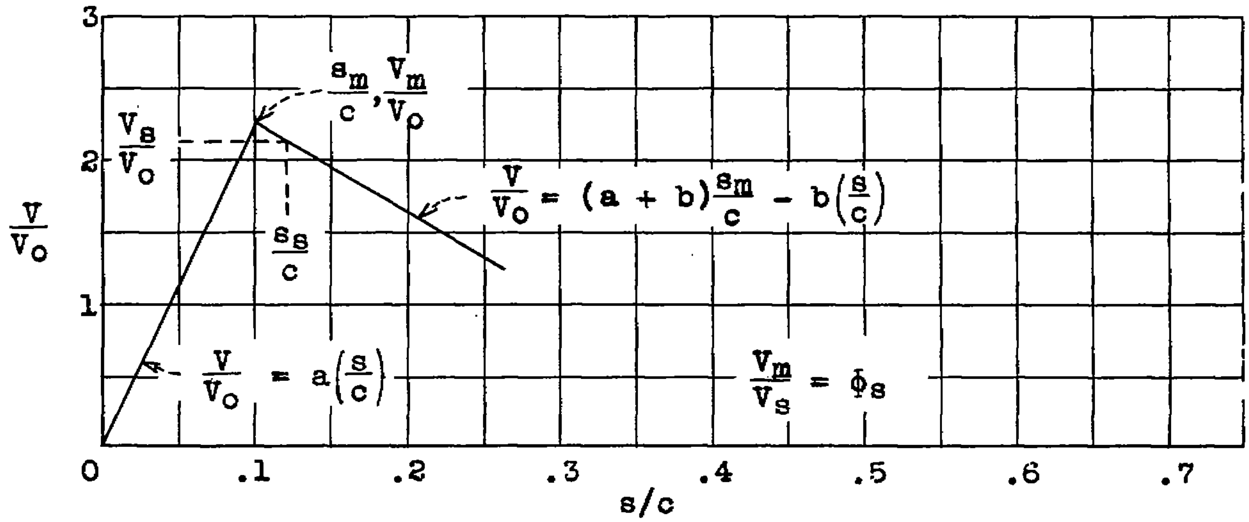


Figure 6.- The effect of roughness density on the equivalent sand grain height.



Double-roof velocity distribution

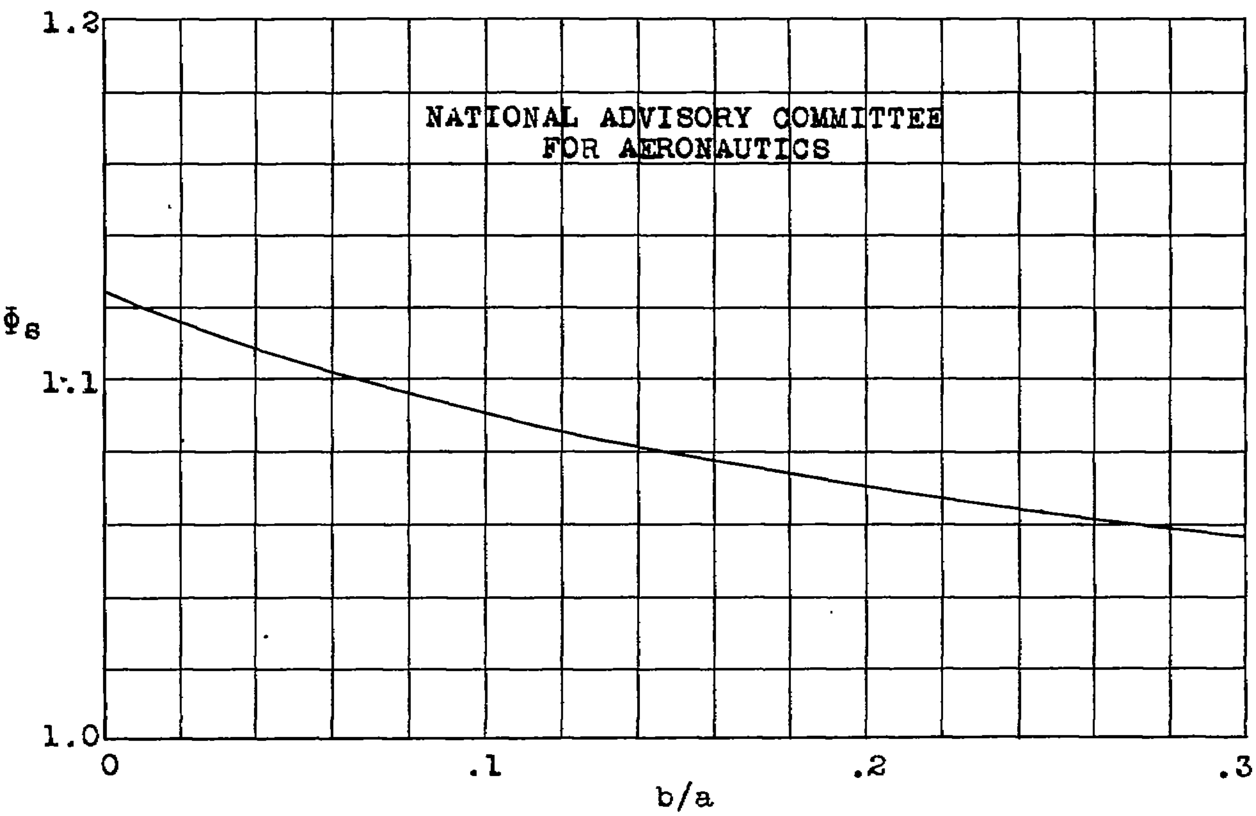


Figure 7.- A function for determining the laminar separation point for a double-roof velocity distribution.